Open surgery simulation of inguinal hernia repair.

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Abstract. Inguinal hernia repair procedures are often one of the first surgical procedures faced by junior surgeons. The biggest challenge in this procedure for novice trainees is understanding the 3D spatial relations of the complex anatomy of the inguinal region, which is crucial for the effective and careful handling of the present anatomical structures in order to perform a successful and lasting repair. Such relationships are difficult to illustrate and comprehend through standard learning material. This paper presents our work in progress to develop a simulation-based teaching tool allowing junior surgeons to train the Lichtenstein tension-free open inguinal hernia repair technique for direct and indirect hernias, as well as to enforce their understanding of the spatial relations of the involved anatomy.

Keywords. Virtual reality, open surgery, hernioplasty, simulation, e-learning

Introduction

An inguinal hernia is an unnatural protrusion of abdominal contents through a weakness in the abdominal wall of the inguinal area. The treatment of inguinal hernias is one of the most common surgical procedures in the US and Europe [1], with open mesh repair being the preferred method of treatment in many European countries [2]. Improvements in patient safety in recent years has lead to increased supervision of training surgeons, which in turn prevents the junior surgeons from performing surgical tasks independently [3]. While these improvements are a clear benefit for the safety of the patients, it increases the burden on senior surgeons and obstructs junior surgeons from gaining the confidence from performing procedures independently [3]. From our literature review and discussions with surgeons, it has become apparent that one of the hardest and most crucial challenges in repairing inguinal hernias is understanding the three dimensional spatial relations of the complex anatomy in the inguinal region [4]. It is our belief that these spatial relations are best taught using three-dimensional models in order to minimize the level of abstraction required by the trainee. A wide range of teaching tools utilizing 3D or pseudo 3D are available for teaching the anatomy of the inguinal region and hernias, ranging from paper cut [5] and plastic models, to simple animation based simulators such as the one provided by Simbionix

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(http://www.etrinsic.com/). However, the level of interaction and user involvement in the currently available tools is restricted.

Our goal is to develop a system that can contribute to the confidence, skills and knowledge of the training surgeons, with a special focus on teaching the anatomy and its spatial relations, as well as the tasks involved in the repair procedure. By doing so, we aim to optimise training by senior surgeons and further improve patient safety by helping trainee surgeons progress through the learning curve faster.

We are building our system around the Lichtenstein repair technique. This technique has been chosen over other open repair techniques due to the wide acknowledgement and scientific evidence supporting it [1]. The ultimate goal is to deploy our system as an e-learning application, allowing surgeons easy access to the application, without the dependence of expensive specialized hardware. Based on our initial analysis and goal, we have arrived at the following overall specifications for our system:

- The system should be web-based and ensure easy and independent accessibility
- The system should require a minimum of hardware - this means no requirements of specialized equipment, such as haptic devices and the possibility to run the application on a standard laptop
- The system should not require supervision to use and only require basic knowledge of the anatomy and the procedure
- The system should be intuitive, allowing trainees to use it independently
- There is a high emphasis on realistic anatomical models and the ability to explore these

The remainder of the paper details the analysis and design of the system, current implementation and results, as well as future planned work.

1. Methods

Our system has been designed around a hierarchical task analysis (HTA) [3], as well as in continuous correspondence with expert surgeons and observations made in the operating theatre. Using a HTA of the Lichtenstein procedure as a foundation, we have compiled an implementation plan detailing A) the virtual environment, B) the user interactions and C) the requirements of deformable models. The implementation plan has then been used to guide the system development according to the overall specifications outlined above. The next sections will cover the use of the HTA, the virtual environment, the user interactions and the deformation models.

1.1. HTA in system design

The HTA is a systematic chronological breakdown of a procedure, detailing tasks, sub-tasks, roles and branching of tasks. We decided to use the HTA as a foundation for an implementation plan in order to have a solid framework for our discussions with surgeons during the design phase of our project. The HTA for the Lichtenstein procedure used here is presented in [3]; it contains 16 tasks and 46 sub-tasks. Since the individual subtasks require various skills, it has been our goal to determine the most suitable implementation for each individual task that would allow our system to convey the crucial details of the surgical procedure. In collaboration with surgeons resident at St Mary's and Whittington Hospitals (London, UK), the HTA was used to iteratively develop and expand the implementation plan on which the simulation system was based.

The final version of the implementation plan encompasses the HTA itself, input from the literature review, observations from video recordings of inguinal hernia repair surgery (eleven open and one laparoscopic), observations from hernia repair procedures (three laparoscopic, two open), and continuous feedback, discussions and input from expert surgeons. The plan contains details on how we intend to implement the 46 sub-tasks of the procedure.

1.2. Environment

Our environment is implemented in Java, using Java3D (https://java3d.dev.java.net/) for 3D rendering. The 3DScience (http://www.3dscience.com/) models by the Zygote Media Group are used as a basis for the anatomical models of skin, muscles, intestine, ligament, bone, blood vessels and nerves. Whilst these models are of high quality and suitable for general visualization and rendering purposes, the level of anatomical detail present does not accurately reflect the anatomy of the inguinal region: the inguinal canal is not present, while the spermatic cord is in a position that bears little resemblance to where it is expected through normal growth and development. We have undertaken the careful modification and extension of the 3DScience models to correctly reflect this anatomy in close collaboration with surgeons. Modification of the 3D models and generation of additional models has been carried out using the Blender 2.5 software package (http://www.blender.org/).

1.3. User interactions

Our implementation plan contains a wide range of different user interactions, such as selection and application of the correct tool, selection from multiple interaction choices (e.g. location of incision), 3D navigation and manipulation and exploring the anatomy.

We have carefully designed the individual interactions to focus on the key elements to be taught to the trainees. For instance, when incising the external oblique muscle, we focus on teaching the trainee *where* to cut, not *how* to cut. As a result, rather than cutting freely, we present the user with a series of incision sites, where the user will have to choose the correct location for the incision, thus allowing the system to easily detect and feedback to the user when he/she tries to perform an incision in an erroneous location. Other tasks, such as the mobilization of the spermatic cord, give the user freedom to drag, twist and explore.

The chronological flow of the procedure is controlled using state machines. The purpose of the state machines is both to ensure that the user does not divert from the correct order of execution of the tasks in the procedure, as well as to determine when the different deformation models should be active or paused to minimize computational load. One general state machine governs the overall flow of the tasks in the procedure, while a number of sub-state machines govern the progression between the different interactions in the procedure.

When the execution of all the state machines comes to an end, the procedure has been completed and the user is presented with feedback on her/his performance. A very important aspect of feedback is to highlight any erroneous actions, together with recommendations of how to execute the same action correctly. Examples of wrong actions could be: placing the polypropylene mesh at a wrong angle with respect to the spermatic cord, or attempting to perform the incision in the skin with disregard to anatomical landmarks.

1.4. Deformation modelling

The anatomy of the inguinal region differs greatly in its geometric and physical properties. We have put much consideration into choosing deformation models that are well suited to handle the properties, geometry and interaction that are required in our simulation system.

The anatomy to be modelled has very different geometries and properties. As a consequence, various models are required to simulate them. They can be categorized in terms of their geometry as follows:

- *Rods* – The spermatic cord and, to some extend the hernia sack, are both cylindrical structures
- *Surfaces* – The external oblique is a very thin surface
- *Volumes* – The layer of skin and fat is a thick layered volume
- *Bundles* – The fibrous net in the inguinal canal consists of a chaotic network of fibres attached to the spermatic cord

The CoRdE or Cosserat rod model [6, 7] was chosen for the spermatic cord as this model encompasses the geometry of the cord, while supporting the necessary pulling and twisting that the cord is subject to while the surgeon mobilises it and explores its contents. Direct and indirect hernias are also modelled using the CoRdE model. We have explored methods for linking the indirect hernia sack to the spermatic cord. One method investigated is the use of simple springs, but Cosserat elements turned out to be a more feasible method. The Cosserat elements allow the models not only move together, but also bend and twist together.

We extended the CoRdE model to a surface in a similar way to the net described in [7] in order to yield the surface models required for the external oblique muscle, and the polypropylene repair mesh. To ensure coherence with the interactions required for the external oblique in our system, we developed a cutting scheme for this Cosserat surface model, which is performed by splitting a control point into two control points and reassigning local elements to ensure no exchange of bending or translational forces between the two points, resulting in the control points coming apart.

Simple individual randomly generated springs were used to simulate the chaotic network of fibres holding the anatomy of the inguinal region in place. Each fibre-spring connects one of the deformation models to the walls of the inguinal canal and holds them in place until the user dissects the fibres.

We chose a spring-based Free-Form Deformation (FFD) model, similar to the dynamic FFD model of SOFA (http://www.sofa-framework.org/), to simulate the deformation and cutting of the skin and the underlying adipose tissue. Cutting is enabled by aligning two spring-based blocks over the incision site, locking the mass points together and letting the user gradually dissolve the locks using a cutting tool.

2. Results

One of our key goals was to make the virtual environment simple and recognizable to the trainees to ensure that they will be able to intuitively understand and interact with it. To achieve this, we have made our virtual operating theatre a close, but simpler, recreation of a real operating theatre. This involved building 3D models of the necessary tools and equipment in the operating theatre. Our virtual operating theatre and adapted 3D models can be seen in Figure 1.

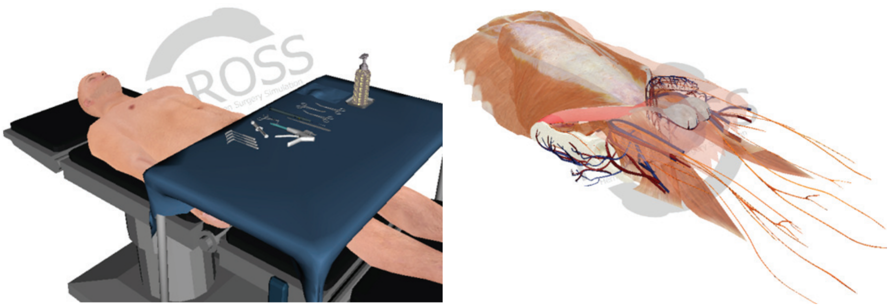

Figure 1. To the left, the initial view of the virtual operating theatre. To the right, the 3D anatomical models, including muscle, vessels, ligaments, bone and facia.

A selection of the various interactions possible is shown in Figure 2.

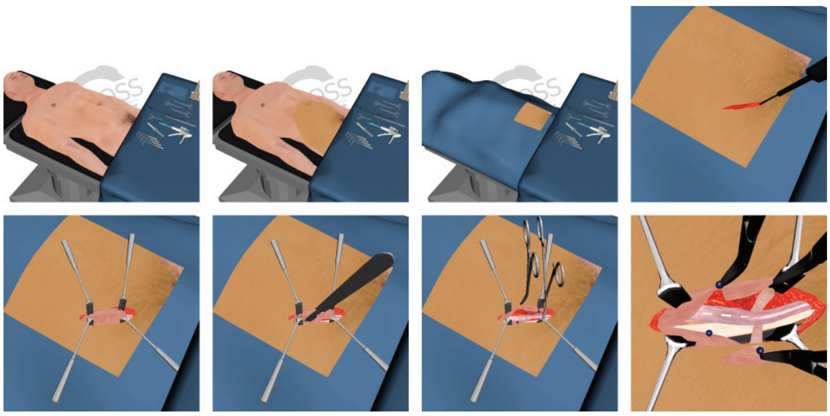

Figure 2. Clockwise from top left: The untreated patient, betadine applied, drape applied, incision in the fat, retraction of the fat, incision in the external oblique, lifting the external oblique with clips, grabbing the spermatic cord.

Based on our experiments, a Cosserat rod model of only twenty elements suffices to define the centreline of the spermatic cord and provide a fast and realistic biomechanical deformation. Our initial validation of this model by surgeons has indicated that it performs in a convincing manner. We have mapped a textured cylindrical mesh and animations onto the model, as shown in Figure 3.

Figure 3. The Cosserat rod based spermatic cord and attached hernia. From the top left: the cord, the cremasteric muscle opened, the hernia partly separated, the hernia separated, the hernia sack opened, the contents of the hernia sack reduced and the hernia sack incised.

The Cosserat surface resulting from our extension of the CoRdE model is highly stable and an abundance of physical parameters allow us to modify the surface to yield the desirable behaviour and configuration. Figure 4 compares the polypropylene mesh and the Cosserat surface subject to gravity.

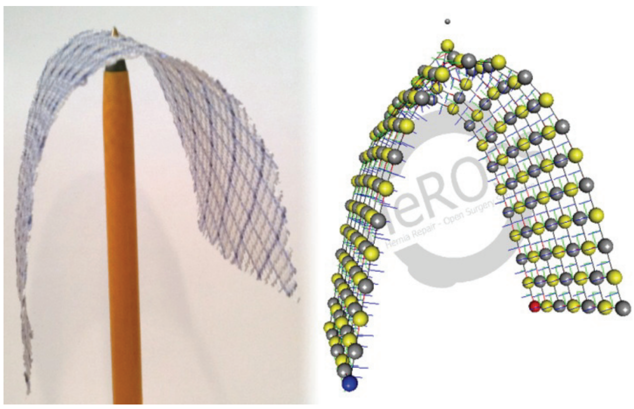

Figure 4. To the left the polypropylene mesh, to the right the un-textured Cosserat surface under gravitational pull. The spheres in the Cosserat surface represents control points, while the grid and lines represents bending elements.

Whilst our method for cutting the Cosserat surfaces described above is limited to splitting control points, it satisfies our needs well, as the correct incision will be pre-defined, and the emphasis is on choosing the correct incision site from a set of multiple possible locations, rather than performing the actual cut manually.

3. Discussion and conclusion

This paper presents the design and initial implementation of a virtual reality system for open inguinal hernia repair. Our use of a HTA in the design and implementation phase of the project assures its clinical relevance and authenticity. The subdivision of the surgical tasks in the HTA proved useful in the design phase of our system - not only did the HTA break down a complex operation to simpler tasks and sub-tasks, it also provided the foundation for useful and productive discussions between clinical staff and developers.

We have found the CoRdE model to be a flexible and powerful model. While the per-element computations are relatively heavy, the model requires only very few elements to handle complex and large deformations. At the same time, the quantity of adjustable physical parameters in the model allows us to simulate a wide range of materials with the same model. Our extension of the rod model to a surface model has resulted in a very stable surface. While the cutting scheme in our Cosserat surface can only be performed at control points, it is suitable for our purposes.

Our future work on this system will encompass further validation and the final stages of development, including summative and formative feedback. Validation of the modifications made to the anatomical 3D models is required to ensure that the models correctly reflect the anatomy of the inguinal region. Validation of the interactions, deformation models, and integrated system to evaluate its value as a teaching and learning tool are all planned. Further development of the tasks involved in the procedure is required to ensure the natural and correct flow of the procedure.

The ultimate aim of this work is to assist trainees progression through the learning curve and, as a result, improve patient safety, the quality of future surgeons, while relieving some of the pressure on senior consultants.

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